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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION U.S.A.

EXECUTIVE SUMMARY

Development of Flat-Plate Solar Collectors for the Heating and Cooling of Buildings

Honeywell

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FOREWORD

This is a synoposis of the final report describing the work performed by Honeywell Inc. for the NASA/ Lewis Research Center, Cleveland, Ohio, under Contract Number NAS3-17862, "Development of Flat-Plate Solar Collectors for the Heating and Cooling of Buildings."

The authors acknowledge the guidance provided by Mr. F.F. Simon, NASA Project Manager, and Mr. R.N. Schmidt, Honeywell Urban and Environmental Systems. Other key individuals include: J.W. Ramsey (Program Manager), J.T. Borzoni, and T.H. Holland.

SUMMARY

The development of an efficient, low-cost, flat-plate solar collector is the essential first step toward the effective use of solar energy for heating and cooling buildings. This report describes a research and development program directed at examining the relevant design parameters in the fabrication of such a solar collector for heating liquids.

The program objective was to design, fabricate, and test a flat-plate solar collector capable of a collection efficiency in excess of 50 percent at an inlet fluid temperature of 93°C (200°F). Furthermore, this collector should be low cost, have high durability, and require little maintenance.

To accomplish these three objectives, Honeywell approached the design task with the use of computer-aided math models of the heat transfer processes in the collector. The computer model was used to determine the preferred physical design parameters from a heat transfer standpoint. This design process aided in defining the absorber panel configuration, the surface treatment of the absorber panel, the type and thickness of insulation, and the number, spacing, and material of the covers.

The outcome of this design task was a collector design and baseline collector, which met the performance goals and which was producible using existing technology. In addition to the baseline collector, variations of this configuration were also identified for further study. These were of interest for a number of reasons. For example, some were predicted to have higher collector efficiency, others would be less expensive to build, while others might have a longer life expectancy.

Prototypes of each of the collector configurations were built and performance tested. All the collector configurations were tested using a solar simulator. The baseline collector and one additional configuration were also tested outside under natural sunlight. Each of the configurations was analyzed to determine the cost differential between designs. This was done both for the fabrication of a limited number of units and also for a limited mass-production level.

Finally, based on the experimentally determined collector performance, simulated operation of the baseline collector configuration was combined with insolation data for a number of locations and compared with a predicted load to determine the degree of solar utilization.

SYNOPSIS OF PROGRAM RESULTS

The design selected for the baseline collector is shown in Figures 1 and 2. This collector plus a number of variations of the basic configuration, was built, tested, and priced. The baseline collector design determined for this program has an aluminum absorber plate with an optically selective Black Nickel coating. The absorber plate is backed with 7.6 cm (3 in) of rigid fiberglass insulation and surrounded with 5 cm (2 in) of rigid fiberglass insulation on its four edges. This absorber/insulation sandwich is encased in a sheet metal box and covered with two layers of glass with a 3-cm (1.25 in) air gap between sheets and a 3-cm (1.25 in) air gap between the absorber and lower layer of glass. The outside dimensions of the collector are 122 x 122 x 15.2 cm (48 x 48 x 6 in).

Honeywell also examined variations of the baseline collector design to evaluate the effect on cost and performance for various collector materials. The variations were concentrated in two major design areas: the absorber and the cover system. Absorber plates were made of both steel and aluminum and coated with selective Black Nickel (steel and aluminum), non-selective black paint (aluminum only), and selective Black Chrome (steel only). The cover systems that were examined consisted of one glass cover, two glass covers, one outer glass-one inner Tedlar, one Lexan cover, and two anti-reflective (AR) etched glass covers. The box design and insulation type and thickness were held constant, as was the cover spacing.

The performance results, determined from the solar simulator testing, indicated that the selective Black Nickel absorber, on either steel or aluminum panel, covered with two sheets of anti-reflective etched glass provides the greatest collector efficiency: 61.5 percent at 93°C (200°F) inlet temperature, 27°C (80°F) ambient temperature, and 100 w/m^2 (320 Btu/hr-ft^2) incident flux.

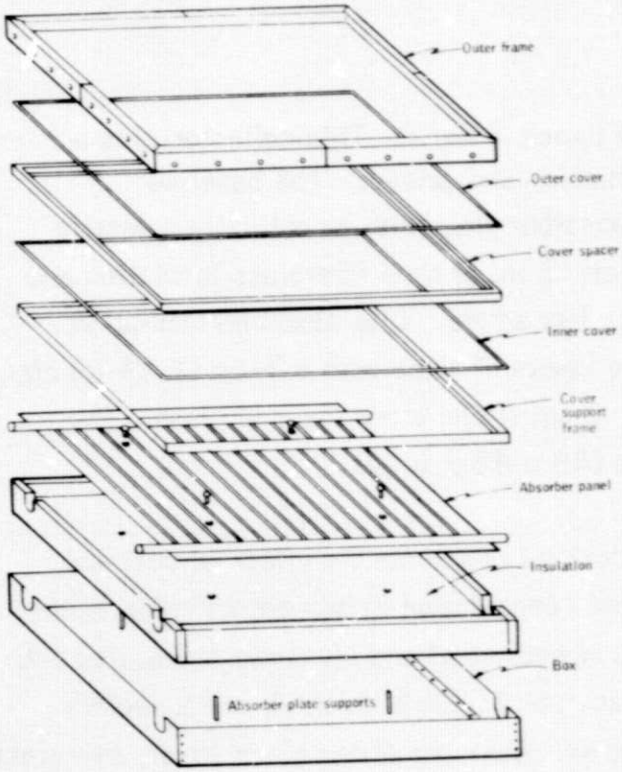

Figure 1. Baseline Collector Assembly

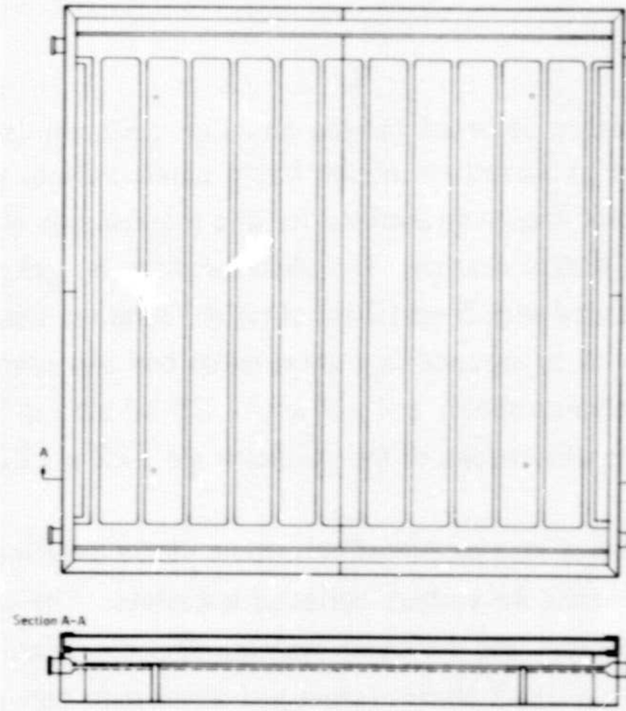

Figure 2. Solar Collector Assembly

Within the bounds of experimental accuracy, the following collector configurations are considered to have met or exceeded the performance goal of 50 percent collection efficiency at the above mentioned input conditions.

- Black Nickel-coated aluminum absorber panel and two glass covers -- 50.5-percent collection efficiency.
- Black Nickel-coated steel absorber panel with two glass covers -- 51.5-percent collection efficiency.
- Black Nickel-coated aluminum absorber panel and two AR etched glass covers -- 61.5-percent collection efficiency.
- Black Nickel-coated aluminum absorber panel and a glass outer cover and Tedlar inner cover -- 52.5-percent collection efficiency.
- Black painted aluminum absorber panel and two AR etched glass covers -- 51.5-percent collection efficiency.
- Black Nickel-coated aluminum absorber panel and a single glass cover -- 49.5-percent collection efficiency.

- Black Nickel-coated aluminum absorber panel and a single Lexan cover -- 49-percent collection efficiency.

- Black Chrome-coated steel absorber panel and two glass covers -- 49-percent collection efficiency.

The following collectors did not meet the design goal:

- Black painted aluminum absorber panel and two glass covers -- 42.5-percent collection efficiency.

- Black painted aluminum absorber panel and an outer glass cover and an inner Tedlar cover -- 40.5-percent collection efficiency.

- Black painted aluminum absorber panel and a single glass cover -- 39-percent collection efficiency.

- Black painted aluminum absorber panel and a single Lexan cover -- 34.5-percent collection efficiency.

Cost was the companion objective to performance. As might be expected, the best performing collector design was also the most costly. A cost analysis performed on each collector design revealed that the greatest cost effectiveness, measured in dollars per unit heat delivered to the working medium, was available from a collector with a Black Nickel-coated steel absorber panel with one glass outer cover and one

Tedlar inner cover. However, only small differences were found in the cost effectiveness of a number of the best units. The top four units had a total cost effectiveness spread of only 13 percent. All of these have selectively coated absorbers. The cost analysis also revealed, as expected, considerable disparity between present costs of fabricating small quantities of collectors, such as 93 m^2 (1000 ft^2) and moderate limited production quantities of 9300 m^2 (100,000 ft^2). Efficiency and cost effectiveness data for a number of collector designs is summarized in Tables 1 and 2. Daily collector efficiencies for a typical summer and winter day for three collector designs is shown in Figures 3 and 4.

Honeywell made estimates of thermal heating and cooling loads for both a house and small industrial building and compared these estimates with the estimates of the amount of solar energy which would be collected by a flat-plate array with an area equal to approximately one half the floor area of the house or building. After making the calculations of the house for nine geographical locations using actual weather data and insolation from a typical year, Honeywell analyzed the industrial building for a single location. We assumed sufficient daytime storage to supplement nighttime heating and cooling, but heat collected in excess of monthly demand was assumed to be dumped, instead of accrued from month to month. Under these assumptions, we constructed Figures 5, 6, and 7 showing that portion of the load which could be supplied by the solar system, which is represented schematically in Figure 8. The total heating and cooling capabilities can then be summarized by the bar graphs in Figures 9 and 10. These graphs indicate that 49 percent or more of the estimated energy required for cooling the house could be delivered by the baseline collector array for all nine geographic locations. With the exception of Minneapolis and Seattle, 50 percent or more of the heating load was also satisfied by the same baseline collector array.

Table 1. Cost Effectiveness for Various Collector Designs

Configuration	Cost effectiveness, dollars		η, percent (a)	$\Delta\eta$, percent
	steel	aluminum		
Baseline (Black Nickel - 2 glass)	1.00	1.00	44.5	
Black Nickel - 1 glass	1.03	1.01	41.5	- 6.7
- Glass/Tedlar	1.13	1.11	46.5	- 4.5
- 1 Lexan	0.92	0.92	41.5	- 6.7
- 2 AR glass	1.03	1.06	55.0	+23.6
Nonselective - 2 glass	0.80	0.93	33.0	-25.8
- 1 glass	0.72	0.83	26.5	-40.4
- Glass/Tedlar	0.79	0.91	30.0	-32.6
- 1 Lexan	0.55	0.64	23.0	-48.3
- 2 AR glass	0.85	0.99	42.5	- 4.5
Black Chrome - 2 glass	0.93	0.93	42.0	- 5.6

[a] At 789 w/m^2 (250 Btu/hr-ft^2), ΔT = 49°C (120°F), and tilt angle = 40°.

$$\text{cost effectiveness} = \frac{\left(\dfrac{\text{Cost/area}}{\eta}\right)_{\text{Baseline}}}{\left(\dfrac{\text{Cost/area}}{\eta}\right)_{\text{Alternate configuration}}}$$

Table 2. Cost Effectiveness for Various Collector Designs

Configuration/cost	η, percent (a)		Cost effectiveness, dollars	
	6/21	12/21	6/21	12/21
Black Nickel - 2 glass	39	29		
\$50.70/m^2 (\$4.71/ft^2) steel			1.00	1.00
\$61.03/m^2 (\$5.67/ft^2) aluminum			1.00	1.00
Nonselective - 2 glass	27	15		
\$47.18/m^2 (\$4.38/ft^2) steel			0.74	0.56
\$48.87/m^2 (\$4.54/ft^2) aluminum			0.86	0.65
Black Nickel - 2 AR glass	50	38		
\$60.82/m^2 (\$5.65/ft^2) steel			1.07	1.09
\$70.94/m^2 (\$6.59/ft^2) aluminum			[illegible]	1.13

[a] Integrated over the solar day.

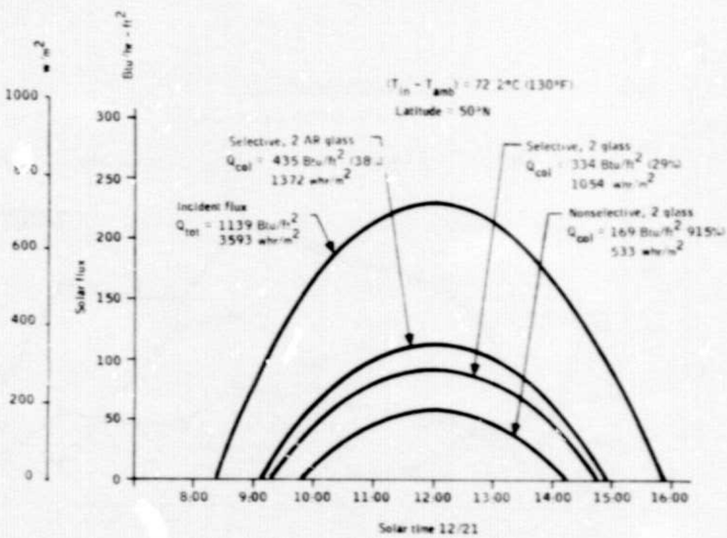

Figure 3. Collection Curves for a Clear Winter Day Insolation

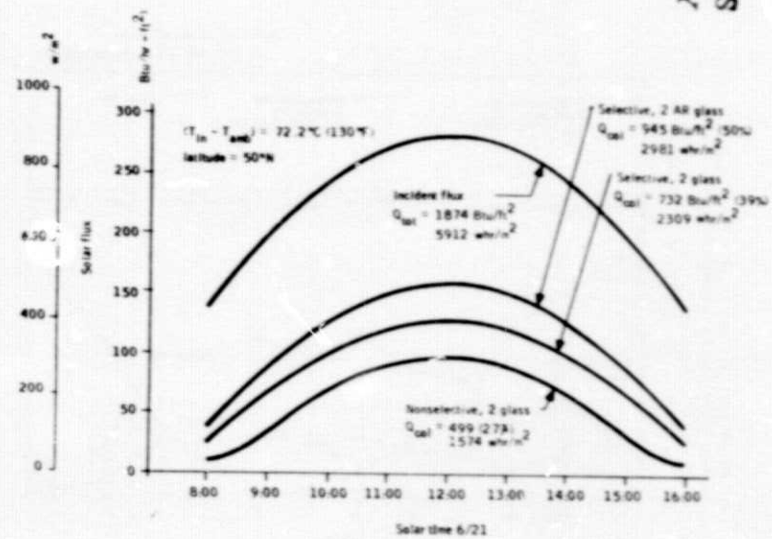

Figure 4. Collection Curves for a Clear Summer Day Insolation

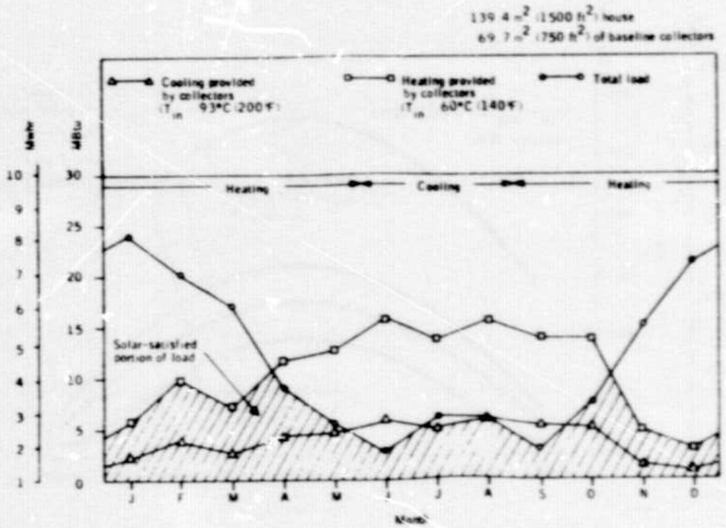

Figure 5. Heading and Cooling Load and Solar-Supplied Portion of a Load for a Minneapolis House

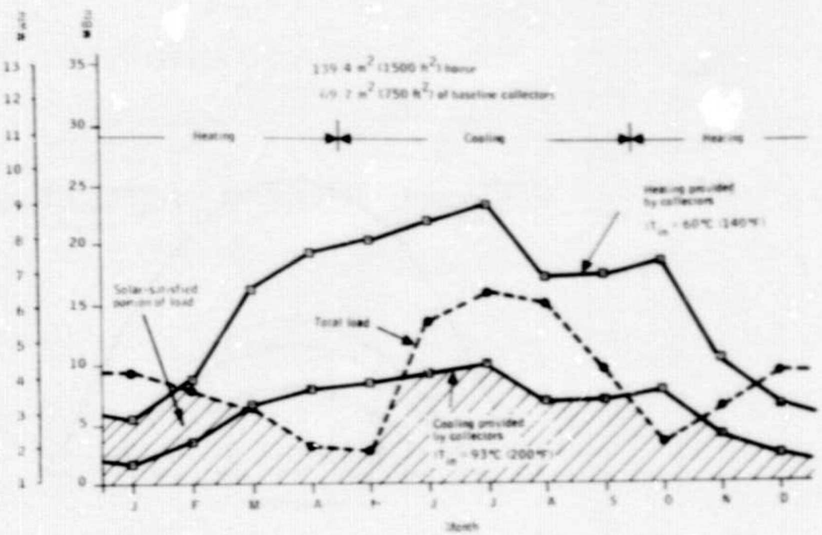

Figure 6. Heating and Cooling Load and Solar-Supplied Portion of a Load for a Atlanta House

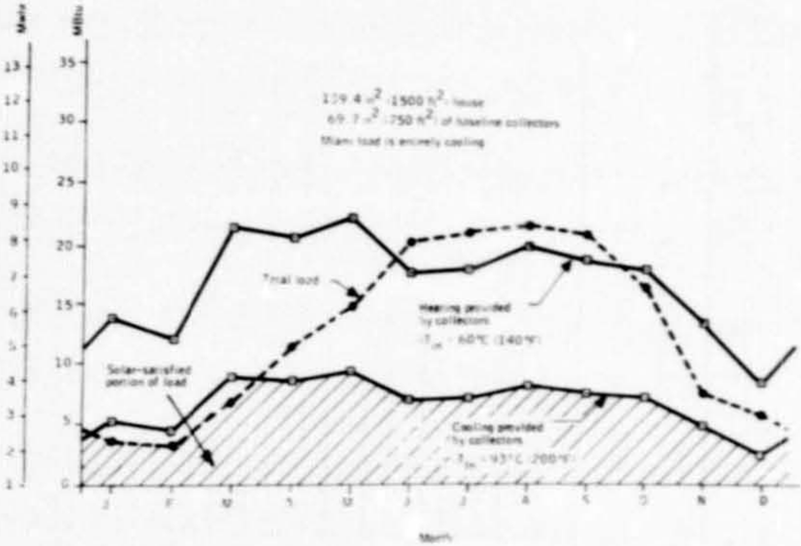

Figure 7. Cooling Load and Solar-Supplied Portion of a Load for a Miami House

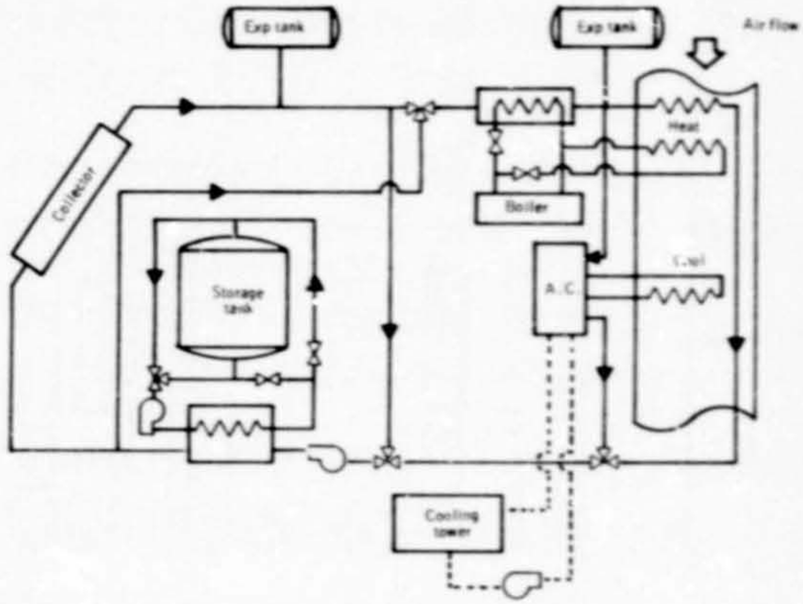

Figure 8. Typical Solar-Assisted HVAC System

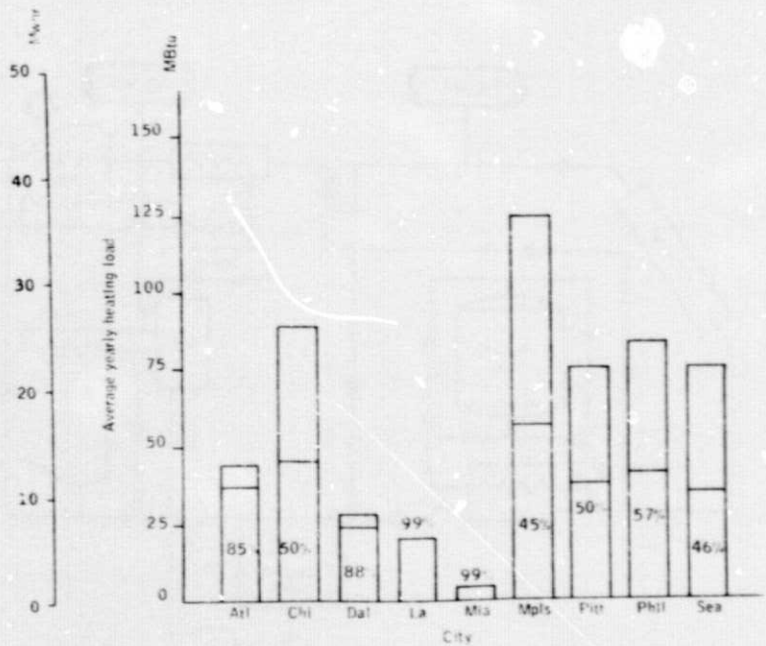

Figure 9. Geographic Comparison of Solar Heating

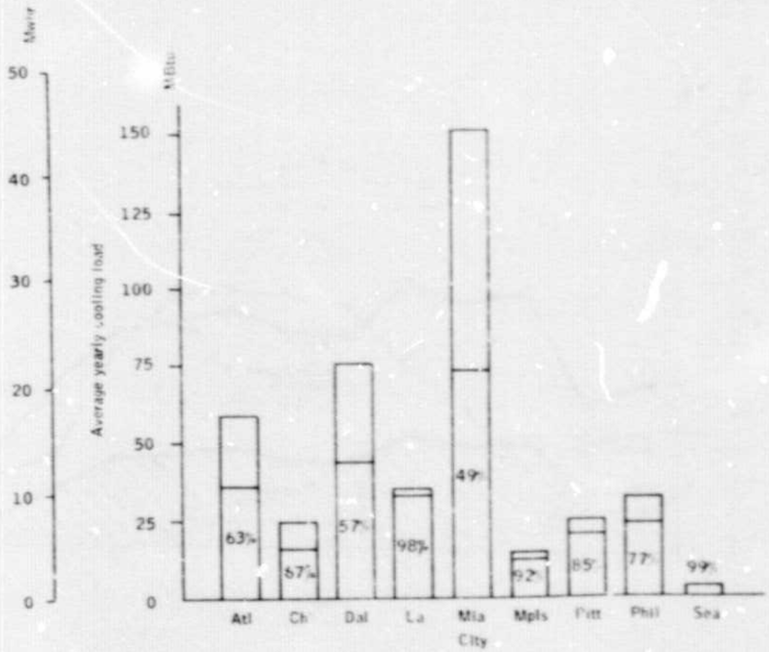

Figure 10. Geographic Comparison of Solar Cooling

A number of important conclusions can be drawn from the analyses and test program, they are:

- The efficiency of the collector is not strongly dependent on the emittance of the absorber plate in the case of small differences between inlet and ambient temperature (~ 72°C or 130°F). This is a typical operating condition for use of the collector with an air conditioner, or a heating application in a cold climate.

- The aluminum and steel absorber plates when coated with Black Nickel had essentially the same performance levels.

- Single-cover configurations are more efficient than two-cover configurations for low-inlet to ambient temperature differences (~28°C or 50° F). (NOTE: The exception to this is the two sheets of AR-coated glass which combined have a higher transmission factor than the single cover sheets tested.)

- Double-cover configurations are more efficient than single-cover configurations for high-inlet to ambient temperature differences (~72°C or 130°F).

- The single versus double cover effects are more pronounced when using the higher heat loss, non-selective absorber surface than when using a selective absorber surface.

- The cover combinations of two glass and one glass/one Tedlar resulted in essentially identical performance.

- The Black Nickel and Black Chrome absorber coatings resulted in similar performance provided that the sooty deposit on the Black Chrome was not disturbed. (Removal of the soot reduces the absorptance from 0.94 to 0.80.)

RECOMMENDATIONS

The analysis and testing completed during the course of this research program indicated that significant improvements in collection efficiency could be realized if appropriate design modifications are introduced to reduce collector heat losses. A solar selective coating could be added to the absorber panel to reduce re-radiation losses through the cover, a second cover layer could be added to the collector to reduce the convection losses through the cover system, insulation could be added around the absorber panel to reduce conduction losses to the housing, and, finally, performance could be increased by applying an anti-reflective surface etch to the covers to allow a greater portion of the incident solar flux to actually reach the absorber panel.

Presuming the design analysis to be correct, concurrent incorporation of all of the above mentioned design modifications should enable collection efficiency to approach the theoretical boundary of performance for conventional flat-plate collectors. As can be seen from the test data, the collector with a selective Black Nickel-absorber coating and two AR-etched glass covers performs significantly better than the other collector design configuration under all combinations of input parameters. Certainly some slight improvements can be made in the performance of this collector. Perhaps the absorptance of the selective coating can be increased to 0.97 or more, and possibly the emittance can be lowered one or two percent; however, these changes are merely a fine tuning of the existing design, they do not hold promise of a significant breakthrough for improving collector efficiency. It is therefore recommended that further investigation be directed in either or both of two directions:

- Reduce life-cycle cost by materials, process, and design development.

- Augment collector performance by non-conventional design modifications, both internal and external to the collector module.

LIFE-CYCLE COST REDUCTION

Life-cycle costing requires an accounting of all costs associated with the total amount of heat flux delivered over the expected life of the collector. This includes not only the first cost of fabricating and installing the collector, but also the cost of the required maintenance, and the cost of renewal or even replacement of collector components, as may be necessary to achieve the expected collector life. Reduction of present life-cycle cost is necessary to improve the economic feasibility of the solar flat-plate collector as an alternate energy source. To achieve the necessary reduction in life-cycle cost, the following areas of study are recommended:

Durability of Selective Coatings

The present selective coatings, such as Black Nickel and Black Chrome, offer a considerable improvement over standard black coatings, in terms of solar performance. However, these selective coatings are susceptible to physical degradation from such sources as humidity and handling. Frequent renewal of a deteriorated absorber coating would seriously impact life-cycle cost over the anticipated 15- or 20-year system life. Additional research and development is required to improve coating durability and extend their normal operating life.

Absorber Panel Corrosion

As has been expressed in the design section of this report, there is some definite concern about the possibility of internal corrosion of the aluminum roll-bond absorber panel selected for the baseline collector design. To combat this corrosion problem and extend the operating life of the absorber panel it may be necessary to perform considerable periodic maintenance, such as adding and changing filters, flushing the absorber panels, and draining and neutralizing the transfer medium. It may even be necessary to change to a different absorber material, such as copper, which will significantly increase the collector first cost. A rigorous investigation of the rates, types and sources of collector corrosion is necessary before the associated cost questions can be answered. Further material studies are also necessary to reduce potential collector corrosion problems.

Cover Material Lifetime

The use of plastic films, such as polyvinyl fluoride or polyesters, for collector covers appears attractive as a means of reducing collector first cost, and also collector weight. However, data on long-term durability, resistance to weathering, and U.V. degradation has not been well established for the plastic films. A study program is recommended to examine the expected lifetime of plastic films. A study program is recommended to examine the expected lifetime of plastic films when exposed to conditions such as temperature and humidity cycling, wind buffeting, and rain and snow loading.

Collector Redesign

As was mentioned in the Cost Analysis section of this report, the baseline collector design is not considered to be optimized from a production level fabrication standpoint. It is recommended that a formal Value Engineering Study be performed in order to redesign the collector to lower fabrication costs and perhaps increase ease of maintenance.

COLLECTOR PERFORMANCE AUGMENTATION

The analysis performed to characterize the thermal processes in flat-plate collector operation has been quite successful in revealing those design parameters which must be controlled to achieve improved collector performance. The requirements for successful absorber design and insulation to improve heat transfer and reduce heat losses are well understood. It presently appears that the area of collector operation least understood is that of the use of the cover system. More specifically, a greater amount of the incident solar flux must be made available to the absorber panel for transfer to the working fluid. Two types of studies are recommended to pursue these objectives:

Reduce Cover System Losses

The collector performance predictions made during the analysis section of this program were consistent in underestimating the amount of collector heat loss. Since the mechanics of the conduction and absorber reradiation losses are well known, it is expected that the convection losses through the cover are actually the

loss component that was underestimated. It is therefore recommended that additional research be performed to more accurately quantify the convection losses, and that design development be pursued to reduce these losses, perhaps through some system of baffling that would disrupt the convection cells without significantly interfering with cover transmission. A second approach might be to evacuate the cover system.

Increase the Insolation Level at the Absorber Panel

The impact of increasing the amount of incident flux that actually reaches the absorber panel can be well appreciated by considering the performance improvement achieved by the use of anti-reflective surface etched glass in the cover system. Collection efficiency increased approximately 10 percent for all combinations of input parameters. This improvement could be further enhanced by the addition of some nonconventional augmentation system to increase the insolation level entering the cover system. One recommended approach that warrants additional study is the use of external reflectors.

One final recommendation may be made with regard to further flat-plate collector development. The cost analysis and utilization study indicated that evaluation of collector performance may be deceptive if only pursued for a limited set of collector input parameters. Installed collector performance under the actual operating conditions of a given geographic location may be significantly different than that empirically predicted from test performance for a limited set of design conditions; different even to the extent that some design modifications may actually be vastly more effective than anticipated, while others may not be effective enough to justify the cost of modification. It is therefore recommended that various collector designs be evaluated for extended periods of operation over the naturally varying environmental conditions encountered in the different geographic areas offered as sites for potential applications.